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– Luncheon Seminar LS-28

3T MRI Cerebrospinal Fluid Dynamics Imaging

– Time-Spatial Labeling Inversion Pulse (Time-SLIP) Technology

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INTRODUCTION

The time-spatial labeling inversion pulse (Time-SLIP) technique developed by Toshiba Medical Systems Corp. has enabled non-invasive observation of blood and cerebrospinal fluid (CSF) in the physiological state by direct labeling with RF pulses. CSF flow imaging is a technique that allows imaging of the movement of CSF using the Time-SLIP technique. This presentation reports on the application of CSF flow imaging to the normal brain as well as diseases such as hydrocephalus, including clinical images obtained with the Vantage Titan™ 3T (to simply be referred to as the Titan 3T).

CIRCULATORY DYNAMICS OF CSF

The circulatory dynamics of CSF is still based on the approach indicated by Cushing, Dandy and Weed et al. in the first part of the 20th century. CSF is actively formed in the choroid plexus. CSF flows from the lateral ventricle into the spinal subarachnoid space from the third and fourth ventricles, and is then passively absorbed into veins from arachnoidal granulations on the brain surface. It has been demonstrated to flow from production sites towards absorption sites in one direction in the manner of a slowly flowing river (unidirectional flow). Cushing positioned CSF as the third circulation after blood and lymph, and the concept of the circulation of CSF has come to be generally accepted.

Recently however, circulatory dynamics differing from this existing concept are becoming clearer as a result of observations of CSF using the Time-SLIP technique.

ADVANTAGES OF DEPICTION OF CSF DYNAMICS BY TIME-SLIP

Known examples of conventional tracer studies of CSF include RI cisternography and CT cisternography using metrizamide. These methods are invasive and not permitting observation in the physiological flow. In addition to the above, the molecular weight and viscosity of the tracer differs considerably from CSF, thus raising doubts as to whether or not these methods are able to accurately reflect the movement of slow-flowing CSF.

Since CSF is desired to be observed in its natural state, the ideal tracer for observing the movement of CSF can be said to be CSF itself. In the Time-SLIP technique, the dynamics of CSF can be accurately depicted since CSF itself is labeled with RF pulses.

Fig. 1 shows an image of a normal brain as depicted by Time-SLIP. In this example of a normal brain, reflux flow, which is a finding that was inherently believed to be associated with hydrocephalus, can be observed in which CSF flows back from the third ventricle to the lateral ventricle.

Fig. 2 shows images of communicating hydrocephalus in the same patient obtained by Time-SLIP (a) and metrizamide CT cisternography (b). Furthermore, findings associated with so-called ventricular reflux, in which CSF flows back to the lateral ventricle, are observed in Fig. 2b, backflow of CSF is not observed in Fig. 2a. On the basis of these findings, it is believed that what is observed in CT cisternography is not the backflow of tracer into the lateral ventricle, but rather the diffusion and mixing of tracer in stagnated CSF that eventually reaches the lateral ventricle. This image clearly demonstrates an extrinsic tracer (contrast medium) does not accurately reflect the flow of CSF.

PRINCIPLE OF TIME-SLIP

Time-SLIP is based on the technical concept of arterial spin labeling (ASL), and is able to use CSF itself as an intrinsic tracer. Labeling of CSF by Time-SLIP consists of first suppressing a background signal with a non-selective inversion recovery (IR) pulse, followed by only inverting CSF at an arbitrary location one more time. When images are acquired after a brief period of time, the labeled CSF flows into the portion of the suppressed background signal and the contrast of the fluid is enhanced, thereby making it possible to depict circulatory dynamics of the CSF (Fig. 3).

The labeling pulse completely recovers in about 8 seconds in the case of a 1.5 T MRI system and observations can be made during this time, when considering contrast attenuation, a more realistic observation time is about 5 to 6 seconds. In other words, waiting about 8 seconds makes it possible to repeatedly examine the same site over and over. This ability to observe the same site non-invasively makes it possible to confirm reproducible results of CSF dynamics. Therefore, this technique resulted in previously unforeseen advantages.

Toshiba's MRI system in particular offers a high degree of freedom when setting labeling position, angle and width (thickness) and allows setting of multiple tags for a high degree of usefulness in the clinical setting. Moreover, development of parameter tuning and other features has been conducted jointly with this hospital so as to optimize CSF imaging.

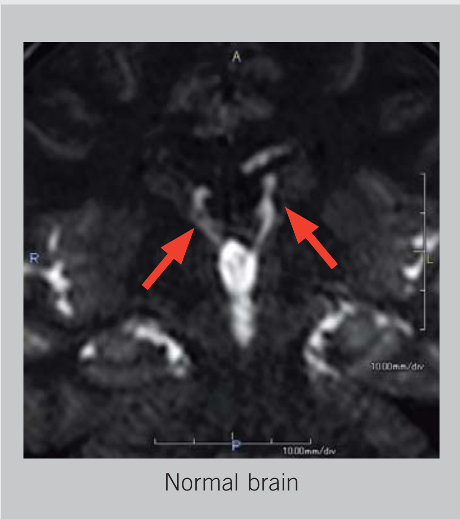

Fig. 1 Depiction of Normal Brain by Time-SLIP

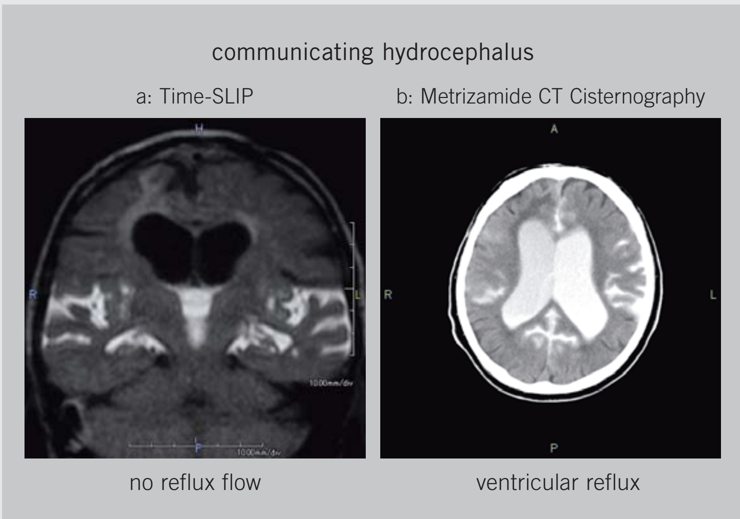

Fig. 2 Images of Communicating Hydrocephalus by Time-SLIP (a) and Metrizamide CT Cisternography (b)

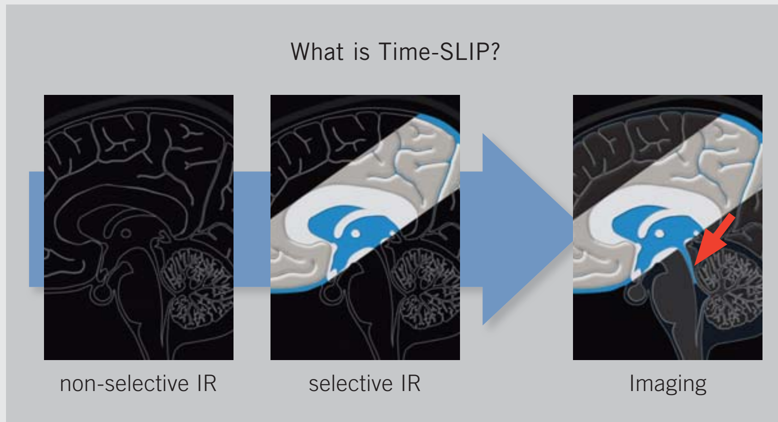

Fig. 3 Principle of CSF Imaging by Time-SLIP

Fig. 4 CSF Flow Imaging by Time-SLIP obtained with Titan 3T

CSF passing through the cerebral aqueduct is depicted with high image quality.

Fig. 4 shows an image obtained by Time-SLIP using the Vantage Titan 3T, CSF passing through the cerebral aqueduct can be seen to be depicted with an extremely high level of image quality. The difference between this technique and conventional phase contrast (PC) techniques is that, in contrast to PC techniques enabling observations to be made for about 1 second in synchronization with heart rate, in the Time-SLIP technique, observations can be made for 5 to 6 seconds. Since observations are made in units of several hours or several days in the case of RI cisternography and metrizamide CT cisternography, being able to depict the dynamics of CSF for about 5 seconds can be said to have been realized for the first time with Time-SLIP.

MOVEMENT OF CSF IN NORMAL BRAIN

First, started with discussion about the movement of CSF in the normal brain as depicted by Time-SLIP.
As shown in Fig. 1, Time-SLIP depicts the backflow of CSF from the third ventricle to the lateral ventricle in the normal brain. This movement differs from that of the classic concept of CSF dynamics employed in the past. However, FLAIR imaging technique frequently demonstrates a flow artifact within the lateral ventricle. Although, this CSF artifact is recognized to be a normal finding, there are no specific descriptions regarding the flow of CSF at this site in many textbooks. CSF dynamics are revealed for the first time by using this Time-SLIP technique.
Fig. 5 depicts the movement in which CSF is agitated in the third ventricle and fourth ventricle. These results were unable to be observed prior to the development of Time-SLIP. This Time-SLIP technique is superior with respect to depicting such turbulence.
When an image of the third ventricle and fourth ventricle is acquired and magnified with the Vantage Titan 3T, refluxing CSF is depicted as colliding with the interthalmic adhesion. While, flow around the lower side of the interthalmic adhesion and flows in the direction of the pineal body on the posterior side. Enabling observations in even greater detail than those obtained with a 1.5 T system (Fig. 6). The ability to study the movement of CSF flow within the third ventricle by using this technique goes beyond the conventionally advocated roles of protecting the brain from external impacts (buoyancy) and serving as a location where waste products are excreted from the brain.
Although the majority of CSF is observed to pass through the Luschka foramen when flowing out from the fourth ventricle in the normal brain, images are obtained in which the CSF occasionally flows out by passing through the Magendie foramen. CSF below the cerebellum and posterior to the brainstem hardly moves, and only circles around towards the front of the ventral side and flows from the ventral medulla into the rapid flow of CSF of the subarachnoid space on the ventral side of the pons.
Fig. 7 shows an image obtained by oblique imaging that depicts the cerebral aqueduct, Monro foramen and lateral ventricle body in the same plane. While a rapid pulsatile flow can be seen in the central aqueduct, only a slow flow can be seen in the lateral ventricle. It should be noted that pulsatile flow varies according to the location in the brain even within the same intracranial environment.
The dynamics of CSF were only able to be observed in animal studies or in a static state due to limitations on detection technology. However, it can be easily surmised that actual CSF demonstrates previously unforeseen dynamics at various positions in the manner of standing, walking or running. Since the Time-SLIP technique makes it possible to observe CSF in the physiological state, new findings are continuing to be obtained indicating that CSF demonstrates dynamics that differ from simple circulation.
Rapid pulsatile flow of CSF can also be observed in the Sylvian fissure. On the other hand, the conventional school of thought has taught the presence of the CSF flow in the portion leading from the Sylvian fissure to the cerebral convexity. Neurosurgeons performing surgery in this region have found that CSF is unable to pass easily through this area of interest. The absence of CSF flow at this site has also been confirmed on MRI images under physiological conditions in which craniotomy has not been performed. The pathway by which CSF is absorbed can be considered to extend from the cerebral convexity through the arachnoidal granulations, yet, CSF in the convexity is stationary. Therefore, flow is not visualized towards these outlet points for CSF. In comparison with pulsatile flow observed in the Sylvian fissure and ventricles, communication may be present over time, but there is substantially no CSF flow. These findings strongly suggest that the principal site of the absorption pathway of CSF is not the arachnoidal granulations. The original understanding of CSF flow has been followed over the past 100 years. Nonetheless, based on these findings with new technology, it is now necessary to reexamine the concept of CSF flow.

MOVEMENT OF CSF IN PATHOLOGICAL STATES

The following describes the movement of CSF in cases of hydrocephalus as depicted using the Time-SLIP technique. In hydrocephalus, the flow of CSF in

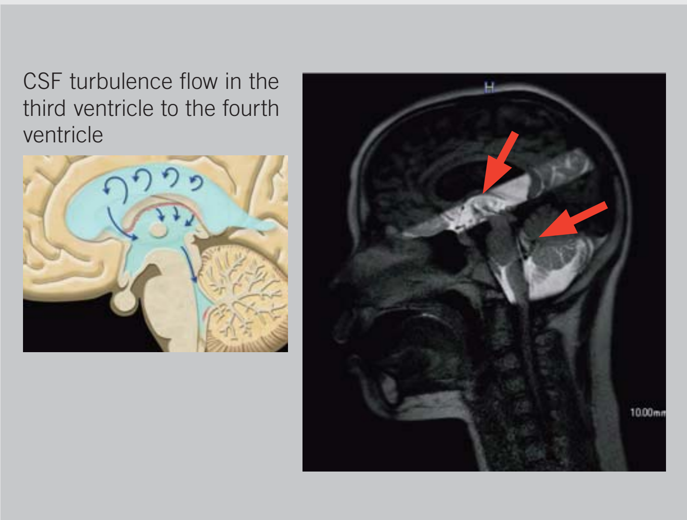

Fig. 5 Turbulence of CSF in Third and Fourth Ventricles as Depicted by Time-SLIP

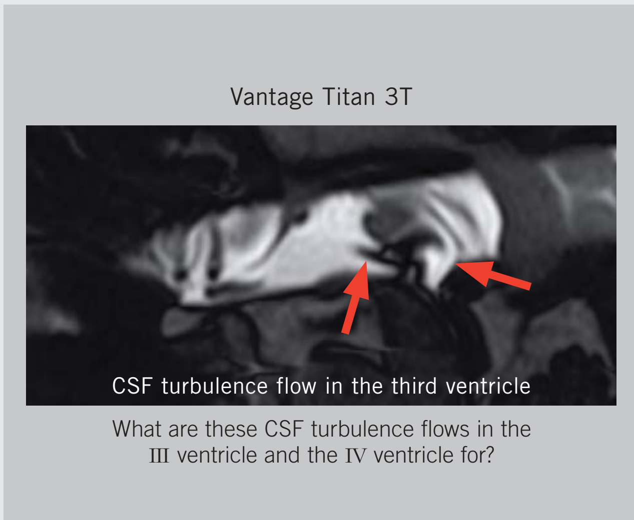

Fig. 6 CSF in Third Ventricle Depicted by Time-SLIP using Titan 3T (Normal Brain)
Turbulence resulting from agitation of CSF is depicted.

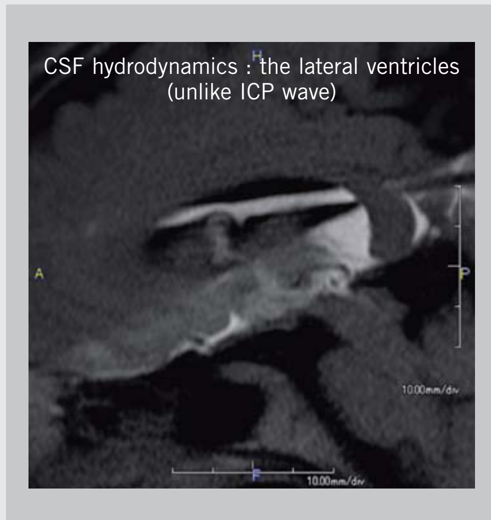

Fig. 7 Oblique Image of CSF by Time-SLIP Depicting Cerebral Aqueduct, Monro Foramen and Lateral Ventricle Body in Same Plane

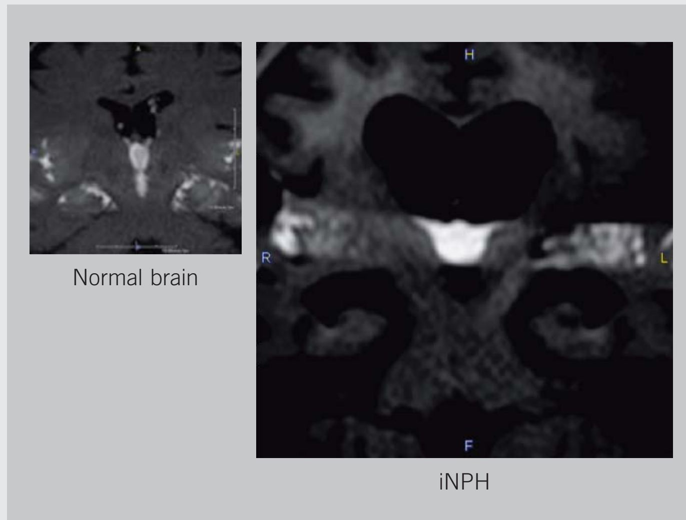

Fig. 8 CSF of Hydrocephalus as Depicted by Time-SLIP
Reflux flow from the third ventricle towards the lateral ventricle is no longer observed.

the central aqueduct tends to be rapid, and reflux flow from the third ventricle towards the lateral ventricle observed in the normal brain is not observed (Fig. 8).

• Hydrocephalus after Subarachnoid Hemorrhage

Hydrocephalus occurring after subarachnoid hemorrhage (Fig. 9) is referred to as communicating hydrocephalus. Reflux flow from the third ventricle to the lateral ventricle has disappeared and the CSF can be seen to demonstrate turbulence in the central aqueduct. In addition, when looking at the flow of CSF in the central aqueduct, the flow can be seen to have changed from laminar flow to turbulent flow, and is understood to be a flow that is not suitable for measurement of flow velocity. Although this condition is unmistakably communicating hydrocephalus in the sense that the circulation pathway of CSF in the ventricles is not closed, aside from issues pertaining to terminology, based on the previous understanding of CSF flow, communicating hydrocephalus attributed to the impairment of CSF absorption in the arachnoidal granulations causing hydrocephalus which occurred following subarachnoid hemorrhage. Actually, subarachnoid space occlusive hydrocephalus is caused by impaired circulation of CSF in the pontocerebellar cistern which is demonstrated with Time-SLIP technology.

• Multicystic Post-traumatic Hydrocephalus

In cases of post-traumatic hydrocephalus, communication of CSF between cysts can be easily observed with Time-SLIP. Fig. 10 shows an axial image of multicystic post-traumatic hydrocephalus in which a single cyst is present in the fourth ventricle, and CSF is depicted as flowing downward, contacting the posterior wall and rebounding off that posterior wall. This depiction of the flow of CSF within a cyst is not possible with techniques other than Time-SLIP. In this case, information indicating that there is communication between each cyst can be determined using Time-SLIP prior to surgery, thereby making it possible to select a treatment method consisting of treating with single V-P shunt only.

• Syringomyelia

In syringomyelia complicated with hydrocephalus (Fig. 11), CSF can be observed to be blocked (communication is interrupted) at the cranio-cervical junction. In an image obtained during occipital decompression surgery (Fig. 11b), it can be seen that the brain stem is relocated towards the dorsal side by surgery to form a space on the ventral side of the brain stem, thereby eliminating the blockage and enabling CSF to begin to flow through that space.

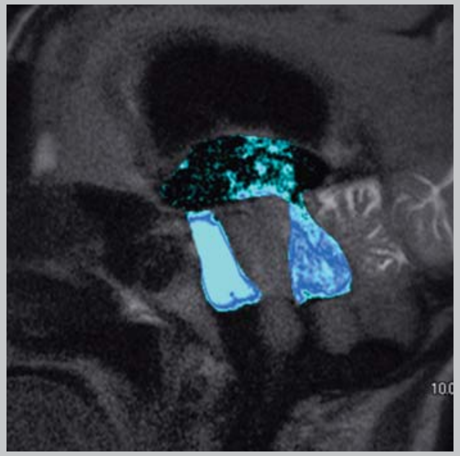

Fig. 9 Hydrocephalus After Subarachnoid Hemorrhage as Depicted by Time-SLIP

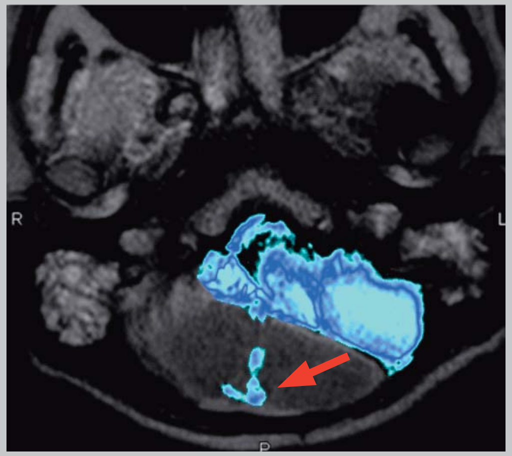

Fig. 10 Polycystic Post-traumatic Hydrocephalus Depicted by Time-SLIP Using Titan 3T

• Aqueduct Stenosis

Aqueduct stenosis is another condition in which the Time-SLIP technique is extremely useful, and enables not only the presence or absence of blockage of the flow of CSF, but also the ability to depict the degree of stenosis, while also facilitating confirmation of fenestration stoma patency following endoscopic third ventriculostomy (ETV) (Fig. 12).

REEVALUATION OF THE 100-YEAR-OLD THEORY REGARDING CSF DYNAMICS THROUGH LEADING-EDGE TECHNOLOGY

Although CSF exhibits turnover and pulsation, the use of the Time-SLIP technique has made it possible to observe multi flowing directions. With the arrival of 3T MRI systems, it has become possible to obtain detailed information on the physiology of CSF flow. The Vantage Titan 3T system and the Time-SLIP technique is expected to lead to a reexamination of the concept behind CSF circulation which existed for the past 100 years.

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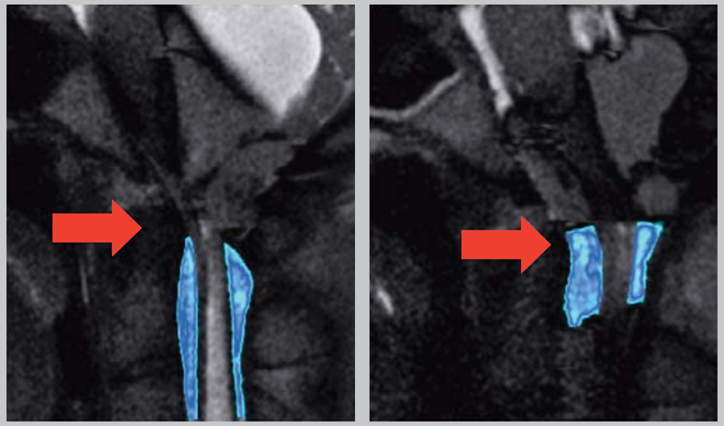

a: Before surgery　　b: After surgery

Fig. 11 Syringomyelia Complicated with Hydrocephalus as Depicted by Time-SLIP

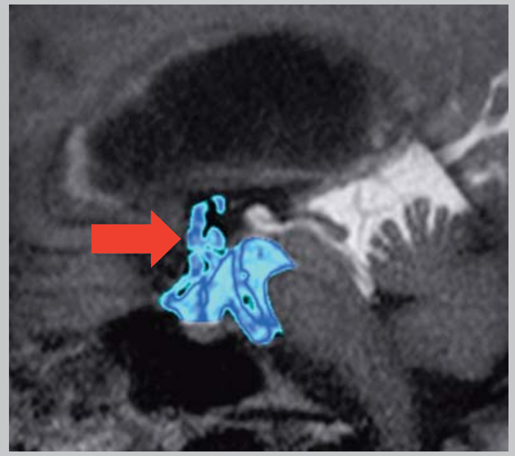

Fig. 12 Observation of CSF Flow after ETV as Depicted by Time-SLIP

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